Decadal Survey White Paper
DRAFT

Dual Satellite Mars Chemistry and Climate Mission Concept
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Background

Tremendous insight gained into the Martian past and present from recent orbiting and landed missions and Earth observations of Mars has prompted further scientific questions about Mars chemistry, astrobiology and climate summarized in the Mars atmosphere group white paper (Mischna et al., 2009). The present white paper presents an innovative dual satellite orbiting mission (DSM) concept designed to provide critical constraints matched to those scientific questions focusing in particular on the remarkable advances that can be made using solar occultations for trace gases and mm-wavelength satellite-to-satellite occultations to probe the near surface environment from space. This effort comes largely from a Mars Scout mission concept called the Mars Astrobiology and Climate Observatory (MACO) that was one of the 10 initial Scout concepts funded for development in 2000. Proposed as a Scout in 2006, MACO received the highest science rating with the reviewers expressing an unusual level of excitement (M. Meyer, pers. Comm.). However, it was assessed as high risk largely because of the challenge of fitting two small satellites into a Scout budget. For this reason, the concept is better suited as a "main stream" Mars mission and we have therefore decided to present the concept here as an input to the Planetary Science Decadal Survey that will define scientific directions for the coming decade. It is extremely important that the Mars community as well as the planetary science community in general understand the new science that can be achieved from orbit using satellite to satellite occultations and consider it in future science mission architecture and design.

Our analysis indicates a multi-satellite approach will provide far better science return at comparable cost than a single, large satellite system for science and future mission preparation/support. The revolutionary advances of a DSM over a single-satellite system include

- *4D characterization of the water cycle*
- *Remote sensing of the near surface environment to observe surface exchange*
- *localization of trace gas sources and landing site selection*
- *determination of near-surface heterogeneous chemistry*
- *wind and atmospheric structure reconnaissance for mission design & operations*
- *redundant telecommunications coverage*

As envisioned, DSM would carry instruments equivalent to or better than the key instruments identified for the Mars Science Orbiter (MSO) including a solar occultation (SO) near-IR spectrometer (nIRS), a combined satellite-to-satellite radio occultation (RO), solar occultation (SO) and thermal emission (TE) millimeter-wave sounder (MMS), a thermal IR ice/dust aerosol sounder (TIDS), a shortwave aerosol sounder (SAS) for estimating particle size distributions and a surface frost spectrometer (SFS) plus a context imager. A copy of HiRise can be flown for surface reconnaissance.

As we will show, this suite provides the *constraining* observations and information to *answer* (rather than merely address) many of the key questions about water, trace gases, and dust and their transport and exchange. We have designed DSM as a **global field campaign** that profiles the chemical, dynamic, thermodynamic and aerosol-opacity state of the atmosphere simultaneously down to the surface as well as the surface below with a global distribution and full diurnal cycle sampling, a combination that cannot be achieved via landers because of prohibitive costs. In fact, the capabilities of DSM exceed anything on Earth but can be achieved in orbit around Mars because of its thin atmosphere.

Like MSO, DSM would carry a *nIRS* that provides high SNR and spectral resolution like the 0.02-cm^{-1} achieved by the Earth–orbiting ACE FTS to **globally survey atmospheric trace species.** In particular this will determine the varying distribution of **methane** and related species to < 1 ppb and significantly better with averaging. *Rapidly precessing, high inclination orbits* provide global SO coverage approximately every 40 days.

What sets DSM apart scientifically are its mm-wavelength satellite-to-satellite occultations. Satellite radio occultation (RO) is a simple, proven technique used since 1965 with Mariner 4 and more recently with MGS, providing precision, accuracy and vertical resolution typically one and sometimes two orders of magnitude beyond that of atmospheric emission observations. Figure 1a shows the ability of MGS RO to profile the near-surface environment and capture the large diurnal variations in temperature there. The RO profiles average horizontally over ~160 km rather than point profiles; thus they do not capture as

much small-horizontal-scale information as point profiles but provide more representative results than point profiles. Figure 1b demonstrates the high vertical resolution achieved with terrestrial satellite-to-satellite RO measurements even at relatively low 1.6 GHz frequencies demonstrating in part why GPSRO was one of the missions recommended in the recent Earth science decadal survey.
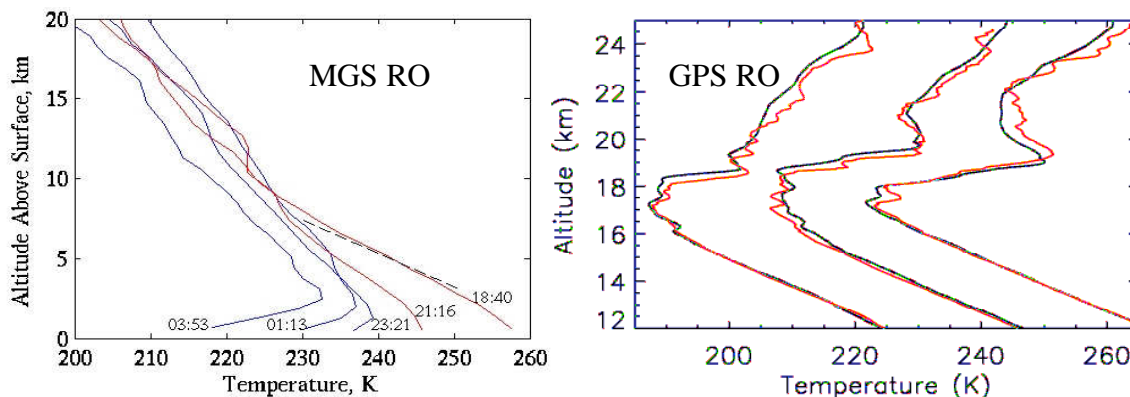

Figure 1. a. Diurnal changes in lower atmosphere thermal structure in between 30°S and 60°S seen in MGS RO measurements (Hinson et al. 1999). *b.* Comparison of close-coincidence GPS RO and balloon profiles in Earth's tropics near the transition between the troposphere and stratosphere demonstrating the vertical resolution of GPS occultations. Black: GPS, Red: balloon. The two profiles to the right are offset by 20 K each.

The satellite-to-satellite geometry and mm-wavelengths bring the full power of RO to bear on many of the Mars atmospheric science questions. As discussed later, answering many of the big science questions requires detailed observations of the chemistry, dynamics and thermodynamics of the **near surface environment** that can only be achieved from orbit via satellite-to-satellite occultations. With 2 satellites in approximately counter-rotating, rapidly precessing, high inclination orbits (compatible with SO needs), satellite-to-satellite dust insensitive mm-wavelength occultations will profile the atmosphere globally with complete diurnal coverage approximately every 44 days. Like the MGS occultations, these occultations will profile density, pressure to 0.1% and temperature to 0.5 K but with 60 m Fresnel diffraction-limited vertical resolution exceeding that of MGS RO by an order of magnitude.

Unlike MGS, these mm-wave occultations will probe the atmosphere with several occultation signals in the 320 to 360 GHz range via differential absorption. Conceptually one occultation signal sits on an absorption line and another sits off to side of the line such that the ratio of the amplitudes of the two signals retains the absorption effect while eliminating common, unwanted amplitude variations such as those due to antenna pointing variations. The absorption measurements will yield profiles of key constituents like H_2O, HDO, CO and its isotopes to 1-3% and H_2O_2, O_3, H_2CO, SO_2, and OCS to ~5 ppb or better. The line-of-sight wind along the direction of the occultation path will be profiled to better than 3 m/s by placing occultation tones on either side of absorption lines of CO isotopes to determine the Doppler shift of the line center, again with 60 m vertical resolution. Also near-surface turbulence, which is critical for understanding surface-atmosphere interactions, will be profiled by the occultations via the scintillations ("twinkling of a star") that result.

The errors noted above are errors of *individual profiles* and will decrease with averaging. The sat-sat occultations are self calibrating in that the signal source is viewed immediately before or after each occultation eliminating long term drift, a critical property for monitoring climate. The RO also provide the information to isolate and reduce the spectroscopic errors *while in orbit*.

This combination of sensitivity, accuracy and vertical resolution is simply not possible with radiometers and will provide approximately ***30,000 globally distributed approximately entry probe quality profiles*** each Martian year. It will routinely and globally profile the boundary layer and exchange between the atmosphere and surface to answer or strongly constrain a number of the key Mars science questions previously thought unachievable from orbit.

Another point is that a properly designed RO receiver can also probe the atmosphere via solar occultation (SO) and thermal emission (TE). This allows near continuous TE coverage of the atmosphere between the sat-sat occultations yielding approximately 200,000 profiles per Martian year.

The approximately 30 cm diameter transmit and receive antennas of the RO instrument require spacecraft pointing to 1 mrad, easily achieved with star trackers. The instrument requires *no new technology* since all of the *required components and assemblies have flown previously in space* and simply need to be assembled into a new integrated observing system. A two aircraft demonstration of the Earth version of this concept, called the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS), is scheduled for spring 2010.

To answer the dust and ice related science questions, aerosols must be measured coincidently with the mm-wave measurements through the diurnal cycle with vertical resolution as similar to the RO measurements as possible. A relatively simple solution is an *uncooled, thermal IR limb emission ice and dust sounder* (TIDS) derived from the Mars Climate Sounder (MCS) *with 2 km vertical resolution* (limited by IR weighting functions) and channels optimized to sample near surface dust under a range of expected dust loading conditions.

To further constrain the coupling between surface and atmosphere, one solution is to measure **surface temperature and any water frost** below each occultation by pointing TIDS and a *near-IR water ice spectrometer* at the surface below each RO profile shortly before or after the RO measurements.

SCIENCE

The Water Cycle

The science investigations and key observations needed to understand the processes and answer questions must be considered in the framework of the moisture balance equation (1):

$$dq/dt = -\vec{\nabla} \bullet \vec{u}q + source_{external} + source_{internal} \quad (1)$$

Terms: 1   2   3   4

where q is the water vapor mixing ratio, t is time, $\vec{u}$ is velocity, *Term 1* is the time-varying 3D water distribution, *Term 2* is the water transport term, *Term 3*, the *source_external*, is the water source from the surface and *Term 4*, the *source_internal*, is the change caused by water condensation or sublimation within the atmosphere. DSM is designed as **a global closure experiment** to measure each term in equation (1).

4D Water Climatology

Insight gained from the latitude vs. season and interannual climatology derived from TES and recent understanding that the Martian orbital obliquity and precession variations likely cause large amounts of water to migrate around on Mars (Head et al. 2003) have driven several interesting and contradictory modeling studies. Determining what is actually happening and why requires that we understand how water varies in the present climate. Specifically, according to the moisture balance Eq. (1), we must begin by measuring q, the water mixing ratio (which has been measured recently by SPICAM solar occultations but not by TES which measures only column water) accurately at the important spatial and temporal scales at which it varies. Earth experience suggests that atmospheric water likely varies over vertical scales of ~10 km to ~10 m. Only mm-wave sat-sat occultations have the sub-km vertical resolution (extending down to the surface) necessary to observe these critical, process-revealing vertical scales.

Table 1: Variables determined by DSM

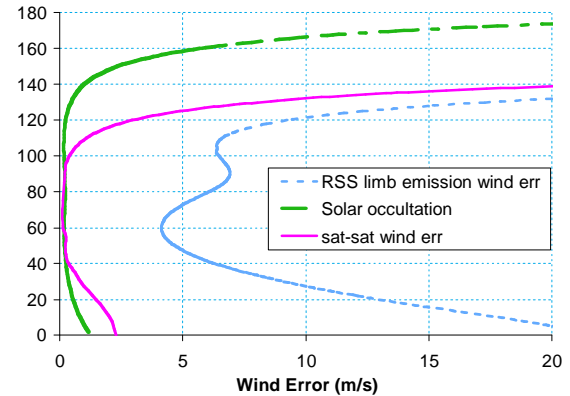| Moisture Variable	Single Profile Accuracy	Alt. Range (km)	Horiz. & Vert. Resolution (km/m)
Concentration	1-3%	0-50	160 / 60–200
Mixing ratio	1-3%	0-50	160 / 60–200
Rel. humidity	4-6%	0-50	160 / 60–200
HDO/H$_2$O ratio	1-3%	0-20	160 / 60–2000
Temperature	≤ 0.5 K	0-50	160 / 60–200
Pressure	0.1%	0-50	160 / 60–200

Figure 2: Accuracy of **individual MACO MMLS Doppler** *wind measurements for satellite-to-satellite and solar occultations and limb emission profiles. With averaging, accuracy improves significantly.*

DSM will determine the four-dimensional (3D spatial plus time) behavior of Martian atmospheric water over at least a full Martian year at key, previously unobtainable spatial and temporal scales and precisions required to reveal unambiguous signatures of climatic processes. DSM's coincident measurements of water, temperature, pressure, HDO and ice, summarized in Table 1, yield a 4D characterization of water in terms of five critical and complementary moisture variables: *(1) Vapor density* (water mass per volume), (2) *Mixing Ratio* (tracer for determining subtle flow pathways through the atmosphere), (3) *Relative Humidity* (related to condensation and sublimation), (4) *Vapor D/H Ratio* (fractionation associated with condensation, photochemistry and subsurface reservoirs), and (5) *Water ice* (transfer between vapor & ice phases).

Water Transport

To determine the transport of water, trace gases and dust requires wind measurements, preferably coincident with the concentration measurements. DSM will **directly** measure line-of-sight (LOS) winds via the Doppler shifts of the lines of $C^{17}O$, $C^{18}O$, ^{13}CO and CO in the ***329-347 GHz*** interval. RO, SO and TE measurements will probe both sides of the line center to determine the Doppler shift coincident with profiling water, other trace gases and dust. The single profile accuracies are shown in Figure 2. Additional constraints will come the pressure gradients determined from the occultations that will enable indirect determination of the balanced portion of the winds. Vertical resolution is critical particularly near the surface to capture expected changes in wind direction and speed.

Meridional transport is central to the water cycling problem because of the primarily latitudinal dependence of water sources (e.g. presence of ice caps only at the poles, strong latitudinal variation of near subsurface water determined by the Odyssey GRS) and the strong seasonal cycle of solar forcing. Meridional transport can be expressed as the correlation of the meridional velocity (v) and the vapor distribution (q), (equation 2) which is the sum of two transport components: 1) the action of the steady, zonal mean meridional circulation on the steady, zonal mean water vapor distribution, and 2) the net effect of zonally and temporally varying meridional winds ("eddies") on the zonally asymmetric and time-varying vapor distribution.

$$\overline{[qv]} = \overline{[q]}\,\overline{[v]} + \overline{[q'v']} \qquad (2)$$

Since the vapor and the meridional wind vary with height (the wind reversing in direction in many cases), these quantities must be vertically-resolved. As such, column-integrated vapor like that from TES cannot be used to make this calculation. MCS combined with a limb-viewing mm-wavelength spectrometer providing line of sight winds could make an important improvement in understanding the vertical distribution and transport of vapor but will be limited by dust dependent retrieval errors and ~5 km vertical resolution that will limit its ability to measure transport particularly near the surface. In contrast, sat-sat mm-wave RO provides the critical measurements of high-precision temperature, pressure, water vapor, and horizontal winds with full diurnal and seasonal sampling and ~100 m vertical resolution in both clear and dusty conditions that are needed to determine the water paths and fluxes, in fact to levels significantly exceeding any remote sensing capability on Earth.

Exchange with subsurface reservoirs

Sat-sat mm-wave RO can measure signatures of water exchange by measuring diurnal variations in the profiles of near surface water vapor and temperature shown in Fig. 3 from which the exchange of water vapor and energy between the surface and atmosphere can be inferred over different regions of the globe. The orbital periods of the 2 satellites can be chosen to provide either random coverage or a systematic repeating pattern at at least 20 locations, providing some of the advantages of a lander network.

Isotopic measurements can answer key questions related to transport such as which reservoirs are exchanging with the atmosphere and whether there is net transfer between reservoirs and the two hemispheres. The HDO/H_2O ratio in water vapor is observed to vary from 2 to 10 over the annual cycle (Mumma et al., 2003; Novak et al., 2005). This ratio decreases as the precipitable water vapor increases over the annual cycle suggesting that water vapor is exchanging with multiple reservoirs with different HDO/H_2O ratios, masses and recycling times (Fischer, 2007). Therefore, by profiling the near-surface HDO/H_2O ratio globally over the diurnal and annual cycles via sat-sat occultations (1-3% to about 20 km

altitude), the variations in the near-surface HDO/H$_2$O ratio can be used to determine the locations and D/H signatures of the different reservoirs that are exchanging with the atmosphere.   Modeling can infer relative sizes and recycling times of the reservoirs thereby constraining their past history and the history of water on Mars. Furthermore, by measuring the HDO/H$_2$O ratio of water emerging from a reservoir and then measuring HDO/H$_2$O ratio of water going into the reservoir later in the annual cycle, one can determine whether there is presently a net flux of water between reservoirs.
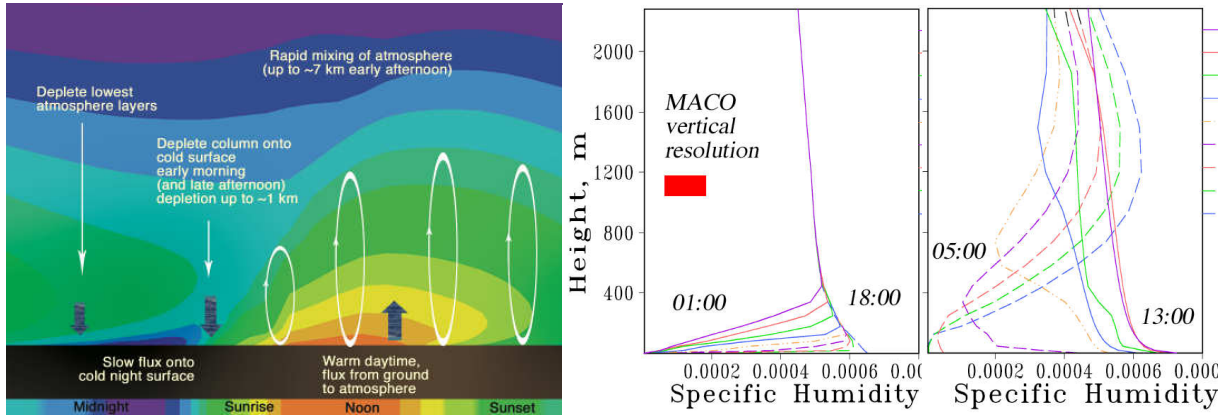

Figure 3 (a) Illustration of diurnal evolution of surface-atmosphere water exchange for L$_s$ = 110°, 22.5° N. Colors indicate temperature scale from 170 K (purple) to 240 K (orange). **(b & c)** Simulated profiles of water mixing ratio in the lowest 2200 m of the atmosphere. Horizontal scale: 0 to 800 ppm. **(b)** Hourly profiles from 18:00 to 01:00 showing the dramatic depletion of water in the lowermost atmosphere as it is transferred into the surface overnight. **(c)**. Hourly evolution from sunrise to early afternoon.

Atmospheric Processes revealed by D/H

Water isotopes also constrain important transport processes in the atmosphere. Globally, and seasonally precise profiles of mixing ratios and temperatures as well as HDO/H$_2$O ratios that extend vertically through the depth of the tropical Hadley circulation will determine whether condensation is indeed limiting the mixing ratios in the upper branch of the Hadley circulation and therefore migration of water to the Southern Hemisphere as proposed by Clancy et al. 1996.

The average Martian D/H ratio in atmospheric water is enhanced by about 5.5 times over that of terrestrial oceans reflecting preferential loss to space of H relative to D, which can be used to constrain the initial H$_2$O reservoir on Mars (Owen et al. 1988, Kass and Yung 1999). In contrast, measurements of H Lyα and D Lyα emission (Krasnopolsky et al. 1998) showed that D/H in H$_2$ in the Martian upper atmosphere is about 11 times smaller than near the surface. Two mechanisms appear to account for much of this substantial decrease in D/H with altitude: i) a reduced photodissociation cross section at wavelengths >170 nm for HDO compared to H$_2$O (Cheng et al. 1999); and ii) fractionation during condensation and evaporation of H$_2$O (Bertaux and Montmessin 2001). Because these fractionation processes are quite large (several 100‰, [or several 10%]), solar and satellite to satellite occultations, with precisions ~10–50‰, will easily detect D/H variations in atmospheric H$_2$O. Simultaneous measurements of HDO, H$_2$O, and the atmospheric temperature profile will allow photochemical and phase change fractionations to be clearly resolved and constrain uncertainties in determining loss rates from the top of the atmosphere and the initial water reservoir. We also note in this context that high vertical resolution close to the surface will be key to separating D/H effects due to different subsurface reservoir sources from D/H variations due to atmospheric processes.

The DUST cycle:

Atmospheric dust has a huge impact on the strength and interannual variability of the Martian circulation, due to its effect on radiative transfer within the thin Martian atmosphere (e.g. Kahn et al. 1992). Feedbacks between surface dust lifting and atmospheric circulation produce significant spatial and temporal variability (Murphy et al. 1995, Newman et al. 2002, Basu et al. 2004), particularly during the 'storm season' (southern spring and summer), making it hard both to predict the atmospheric state for a

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given storm season and to infer how the circulation may have differed in past orbital epochs. The direct (radiative) and indirect (dynamical) effect of dust on atmospheric temperatures also impact in a major way the present water cycle and its evolution over geologic time, as do dust particles acting as condensation nuclei for water ice (affecting radiative heating, scavenging of dust to form condensation nuclei and surface deposition rates of both dust and water). MGS TES observations of dust, ice and water vapor (Liu et al. 2003, Smith 2004) show differences between years with and without major dust storms (such as lower vapor abundances over the summer pole during a global storm). As yet the available data sets are inadequate for us to understand fully the processes producing this behavior. DSM measurements will address the following science questions related to dust and its impact on the water cycle:

What determines where and when dust storms originate? Despite recent progress in modeling Martian dust storms (Newman et al. 2002, Basu et al. 2004, Kahre et al. 2005), models remain unable to capture the full range of storm types and interannual variability. The best (perhaps only) way to improve our understanding is to measure the near-surface atmospheric state (particularly winds, wind shear, turbulence, and stability provided by mm-wave RO) at the *same time and location* as changes in dust abundances (which can then be linked to injection rates). For example, DSM should observe a distinctive afternoon peak in dustiness if dust devils are the dominant source.

What determines dust storm decay rates? Models seem unable to capture the relatively rapid decline of global dust storms observed on Mars, possibly because they don't account for enhanced scavenging by water ice during this period, a hypothesis that DSM measurements of dust and water ice would test.

How do regional and global dust storms affect the detailed circulation and water transport? The revolutionary sensitivity and resolution of the combined DSM temperature, wind, dust and water observations will enable us to study this in detail and help us understand whether large dust storms alter the distribution of water and its inter-hemispheric transport.

Trace gas inventory

The discovery of methane on Mars has dramatically raised the priority of understanding Martian chemistry and tying it to subsurface geochemical and possible biogenic sources. Determining the trace gas inventory of the Martian atmosphere requires accurate measurements of a number of key constituents many with mixing ratios of the order of 10 ppb or less. The best solution is a near IR solar occultation spectrometer ('NIRS') such as the French SOIR instrument or the Canadian fourier transform spectrometer (FTS) instrument on the Earth-orbiting Atmospheric Chemistry Experiment (ACE) (Bernath et al. 2005) that measure the spectra of a wide range of species to sub-ppb levels. Millimeter wavelength observations can supplement these and provide cross-validation. As noted, both SO and RO require high inclination, rapidly precessing orbits.

Locating sources of plumes

Determining whether the source of methane is geochemical or biogenic likely requires placing a lander near the source of a methane plume. Determining a source location potentially anywhere on the globe requires tracing an observed plume back to its source which requires a detailed knowledge of (1) winds and (2) mixing caused by turbulence.

Ultimately, the best estimates of plume source locations will come from plume dispersal reconstructions derived from atmospheric state estimates produced by a numerical weather data assimilation (DA) system which combines an atmospheric model with observations to initialize and steer the model. The quality of such estimates depends critically on the model's realism which to a large extent is as good as the observational constraints used to evaluate the model. Such constraints must include profiles of wind and turbulence at resolutions sufficient to determine important features relevant to advection and mixing. As on Earth, boundary layer winds are undoubtedly complex, exhibiting sharply defined vertical changes in speed and direction that are functions of albedo, thermal inertia, topography, season, weather and diurnal cycle. As confirmed by the Phoenix LIDAR, these scales are far too sharp to be resolved by 5 km vertical resolution of a mm-wave radiometric spectrometer which together with 5 to 20 m/sec precision (Figure 1) will limit the impact of such observations on plume source reconstructions. In contrast, the nearly 2 orders of magnitude better vertical resolution and 1 order of magnitude better precision of RO profiled line-of-sight winds profiled together with mixing ratios, potential temperature

and turbulence within and above the boundary layer will provide the quantitative constraints at scales and precisions unimaginable with emission measurements needed to evaluate and improve models, hold DA state estimates close to reality and determine how methane and other constituents are dispersed.

Heterogeneous chemistry

The recent detection of CH_4 in the Martian atmosphere from ground-based telescopes reported in Mumma et al., 2009 argues for a dramatically different chemistry for CH_4 than has generally been assumed (e.g., Summers et al. 2002). Apparent spatial and temporal variations in CH_4 abundance argue for a CH_4 lifetime $<<$ 6 months, at least 3 orders of magnitude shorter than the photochemical lifetime (due to reaction with OH) of 300 years (Summers at al.).

It has been proposed that the highly oxidized state of the surface and greatly elevated local CH_4 loss rates can arise from ion production associated with dust charging (Atreya et al. 2006; DeLory et al. 2006). Dissociative electron attachment (DEA) reactions yield elevated levels of OH (from H_2O) and CO (from CO_2) in the vicinity of the dust storm. The OH either directly reacts with CH_4, or combines to form H_2O_2 that deposits on the surface and destroys CH_4 in heterogeneous reactions. In either case, highly elevated, local H_2O_2 abundances are predicted (Atreya et al., 2006). Because the standard photochemical models (e.g., Nair et al. 1994) reproduce (actually predicted) the column density of atmospheric H_2O_2 very well (Encrenaz et al. 2004), the dust storm DEA chemistry can only operate locally. Support for the dust charging scenario comes from observations of microwave emission from Mars during a dust storm (Renno et al. 2003). More recent considerations (unpublished) of dust charging during a dust storm argue that charge separation occurs primarily between saltating grains and small easily lofted grains. Discharge occurs over distances ~10 cm due to the near optimal atmospheric pressure for discharges. This restricts dust charging effects and associated DEA chemistry to the atmospheric boundary layer (whose depth varies over the diurnal cycle: see Fig. 3) and perhaps much closer to the surface depending on the lifetime of the H_2O_2 because reaction rates depend strongly on the field strength which may be highest within a few cm of the surface.

Heterogeneous DEA production of OH/H and subsequent generation of H_2O_2 also depend on the amount of water vapor present such that the efficiency of heterogeneous chemistry may be quite variable. Concurrent measurements of H_2O and H_2O_2 are therefore critical to understanding the near-surface heterogeneous electrochemistry.

Direct confirmation of the products of DEA chemistry, H_2O_2 in particular, requires observations of the chemical products in a dusty environment with a vertical resolution no worse than the extent of the boundary layer and preferably much smaller. A nIRS has limited ability to probe through dust. A mm-wave limb emission spectrometer is limited by its $\geq$5 km vertical resolution as well as its inability to probe right to the surface because of sensitivity to varying surface emissivity. Satellite-to-satellite mm-wave occultations will profile H_2O_2, H_2CO and H_2O, as well as winds, turbulence and temperature, with ~100 m vertical resolution down to the surface over the entire diurnal cycle while TIDS simultaneously determines the amount of dust and ice present. This information will determine how H_2O_2 concentrations and other chemical constituents vary in the near-surface environment as functions of dust and water vapor in particular as well as winds, turbulence, boundary layer depth, temperature and stability and determine whether hypotheses involving dust and electrostatic discharge chemistry are indeed the missing CH_4 loss mechanism and how that mechanism depends on conditions.

Contributions to Mars Infrastructure

The two satellites provide redundant telecommunications relay such that if one satellite is lost the telecom capability remains (unlike a single orbiter where if a satellite is lost, everything is lost). The meteorological observations provide density for aerobraking at high altitude and low level winds and turbulence for EDL. By adding X-band receiver front ends to the RO instrument, the two satellites could provide the beginnings of a precision navigation network like GPS at Mars.

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